White Paper #5

Ecological Forecasting

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I. Description of the Issue

The health of the U.S. economy is inextricably linked to the health of our Nation's ecosystems and the goods and services they deliver to our economy. Each year, U.S. ecosystems provide over $227 billion in added value to the U.S. economy (CENR, 2001) as well as other harder-to-quantify services and benefits such as waste detoxification and decomposition, air and water purification, maintenance of biological diversity, and recreational and spiritual renewal (Daily et al., 1997). Coastal ecosystems, in particular, provide a wealth of fisheries resources and recreational benefits, and are a potential source of life saving pharmaceuticals. These important ecosystems can also directly impact human health from exposure to contaminated water (e.g., from urban and agricultural runoff, pollutants, coliform, and other pathogens, and toxic algae) or contaminated food (e.g., fish and shellfish).

Sustaining productive ecosystems, and restoring damaged ones, depends on the ability to understand and predict the impacts of human activities and natural processes on those systems and to forecast ecological change. Policy makers, natural resource managers, regulators, and the public often call on scientists to estimate the potential ecological changes caused by these natural and human-induced stressors and to determine how those changes will impact people and the environment. During the last decade, using technological and scientific innovations, scientists have developed and tested forecasts in ways that were previously not feasible (Clark et al., 2001), signaling the emergence of a new and challenging science called "ecological forecasting."

What is Ecological Forecasting?

Ecological forecasts predict the impacts of physical, chemical, biological, and human-induced change on ecosystems and their components (CENR, 2001). Extreme natural events, climate change, land and resource use, pollution, and invasive species are five key drivers of ecosystem change (CENR, 2001) that interact across wide time and space scales (i.e., hours to decades and local to global) (Figure 1). Ecological forecasts aim to understand, predict, and provide information to mitigate the impacts of these stressors on ecosystems. In much the same way that a weather or economic forecast can help society plan for future contingencies, an ecological forecasting capability is necessary for environmental managers to make informed decisions regarding alternative management scenarios and to take appropriate actions to affect those conditions and better manage the Nation's coastal resources. Ecological forecasts give managers the tools to answer "what if" questions about the ocean and coastal environments and provide a bridge between science and policy. Ecological forecasts also have the potential to provide widespread societal and economic value to the country. These values include improved decision-making for coastal stewardship; mitigation of natural events and human activities (e.g., land-use practices, fishing); reduced risks to human health; reduced impacts of natural hazards; enhanced communication among scientists, managers, and the public; and overall, more effective prioritization of science.

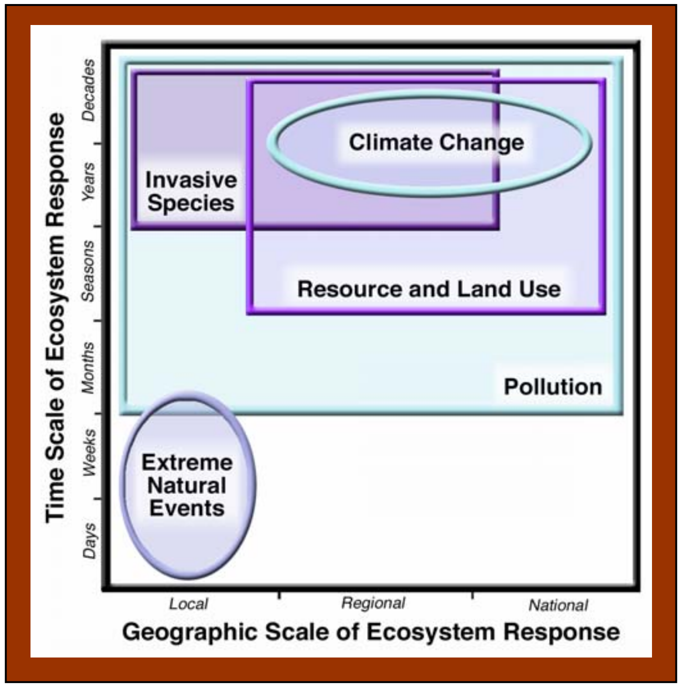

Figure 1. Time/Space Scale of Ecosystem Response. The five key ecosystem stressors – pollution, land and resource use, invasive species, extreme natural events, and climate change – can challenge the integrity of ecosystems and impede the delivery of their goods and services. These stressors can act alone or together, and their cumulative effects are poorly understood. Ecosystem responses are as varied as the inputs that strain them, playing out in scales from hours to decades and from local to global. Figure is reproduced from NOAA Technical Memorandum NOS NCCOS 1, p. 2

Types of Ecological Forecasts

There are many types of potential ecological forecasts. Some will be predictions of what is likely to happen in a particular location in the short-term like weather forecasts (e.g., sea nettle swarms in the Chesapeake Bay, the landfall of harmful algal blooms (HABs), beach closings, drinking water quality, the movement of oil spills, and coral reef bleaching events). Others will focus on much longer-term and larger-scale phenomena (e.g., year-to-year variation in fish stocks, extinction risk of endangered species, new invasive species encroachments, rates of habitat restoration, effects of climate change on biota, and water quality and quantity).

Specific issues within each of these categories of stressors are listed below:

Extreme natural events – Such events may include extreme changes in water resources, severe spring storms and hurricanes, extreme climate variation (e.g., an exceptionally cold or warm year compared to the average), shifts in marine populations, hypoxic/anoxic events, and toxic algal blooms. The ability to predict the occurrence of these events and their ecosystem effects, as well as their interactions with other causes of change, is important for planning management and response activities.

Climate change – Climate change may include changes in sea level, large-scale ecosystem drivers (e.g., current patterns, storm tracks and frequency), nutrient flow regimes and the extent of "dead zones", the amount of precipitation, and river flow. Climate change may be reflected as a change in the mean or trend of a parameter, shifts in seasonal cycles, or extreme natural events (e.g., coral bleaching, ENSO). To plan for and minimize impacts of these events, resource managers need forecasts of the interaction of climate change and variability (e.g., in sea surface temperatures, freshwater input, coastal nutrients) with other stressors on ecological integrity; goods and services (e.g., fisheries, water quality and quantity), particularly the distribution and abundance of species; production of ecologically/economically important species; and the availability of clean water.

Land and resource use – Human use of land and resources can dramatically change the structure and function of an ecosystem. Fishing, for instance, can remove predators or prey in the food web, which may then cause changes in the abundance of less desirable species, some of which can cause a degradation of the overall quality of the system. The ability to predict the ecosystem consequences of various levels of fishing effort is critical for the management of ecosystem resources. Additionally, changes in coastal ecosystems may be linked to changes in land and resource use which are often associated with agriculture or local urbanization as well as the resultant nutrient loadings and deterioration of coastal habitat. Current needs include forecasts of changes in the health and productivity of ecosystems that are critical in providing food and recreation.

Pollution - Concerns about the presence of potentially harmful chemicals and excess nutrients in the environment remain a top concern. Current needs include forecasts of the effects of air pollution and land-based activities (e.g., agricultural production, forest harvest, urban growth and residential development, waste disposal, toxins) on aquatic ecosystems. The damage to the ecosystem may be direct (e.g., hypoxia/anoxia, HABs), or may impact its goods and services (e.g., contaminated fish and shellfish).

Invasive species - Invasive species are species that are introduced intentionally or accidentally from other geographic areas, and are capable of spreading rapidly and replacing native species. These invaders exist in nearly all U.S. ecosystems, pose potential threats to the integrity of biodiversity and ecosystems, and cost billions of dollars annually to mitigate. Current needs include forecasts of the conditions favorable to the introduction, spread, and ecological impacts of potential and already-introduced species.

Interactive and cumulative effects – Large aquatic ecosystems are subject to multiple causes of ecological change. For example, an extreme natural event may provide opportunities for new species invasions, and the success of that invader may be enhanced by altered climate (new precipitation and temperature patterns), use of land and related resources, and the level of pollution in the environment being invaded. The cumulative impact of threats may be greater than the sum of individual impacts. Building the ability to forecast the cumulative effects of these multiple stressors is one of the most significant challenges for applied ecology.

Thus, ecological forecasts can span a wide range of issues and space/time scales, reflect a diverse user community, and involve a multitude of biological factors (e.g., life history traits, behavior, species, population and ecosystem interactions) as well as physical and chemical factors. Ecological forecasts can also involve predictions that are independent of time and involve "scenario testing" or examination of alternative management scenarios (e.g., impacts of nutrient reductions, the setting of harvest levels, and ecological effects of sea level rise). Models are often used to conduct forecasts, but these are just one of many tools (e.g., satellites, sensors, test kits) that can be used and integrated to provide valuable ecological forecasts for management applications.

NOAA's Role in Ecological Forecasting

Ecosystem forecasts have been gaining momentum for the past few years, particularly among academics (Clarke et al., 2001) and Federal agencies (NOAA, 2001). The National Science and Technology Council's Committee on Environment and Natural Resources report on ecological forecasting (CENR, 2001) stressed the Nation's need for developing forecasts of ecological change. Since 2001, NOAA has formalized the development of an ecological forecasting capability for resource managers through a partnership across all NOAA line offices and with universities and other Federal agencies across the country. The report of the U.S. Commission on Ocean Policy (USCOP, 2004) also highlights the importance of ecosystem-based management and its reliance on the development of predictive capabilities for ocean ecosystems, providing further justification for NOAA to undertake ecological forecasting to support its ecosystem-based management responsibilities.

NOAA has recognized the importance of ecological forecasting by including the development of prediction and forecasting tools as high priority areas it in its recently published five-year and 20-year research plans. In the NOAA five-year plan, the development of routine forecasting products for issues such as fish stock assessments, HAB forecasts, beach closings and water quality are listed as part of an "end-to-end" ecological observing system capable of providing these forecasts for resource managers and the public (NOAA 2005b). In the NOAA 20-year plan, ecological forecasting related products are highlighted prominently in the list of example NOAA products and services for 2025 (NOAA 2005a). These include: forecasts and mitigation strategies related to: anoxia/hypoxia, harmful algal blooms, beach closings, invasive species, waves, air/water quality and quantity; ecological assessments and predictions of impacts from climate change (e.g., coral bleaching); decision support tools for adaptive, ecosystem-based management of fisheries, coastal development, and marine resources; improved assessments of sea level change on coastal resources and ecosystems; fishery productivity forecasts that incorporate the effects of climate change.

A dedicated ecological forecasting capability is critical for the agency to achieve the mission and goals set out in the NOAA Strategic Plan (NOAA, 2004) to “understand and predict changes in the Earth’s environment and conserve and manage coastal and marine resource” (Mission Statement); “protect, restore, and manage the use of coastal and ocean resources through ecosystem–based management” (Goal 1); and “increase its investments in short-and long-term research in development of advanced technology to understand, describe, and predict changes in the natural environment” (cross-cutting priority). In the NOAA FY 2007 Annual Guidance Memorandum (NOAA Program Planning and Integration, 2005), language supportive of ecological forecasting is included in the sections on integrating global observations; advancing NOAA’s modeling capability; providing leadership for the oceans; increase climate information, services, and products; and providing critical information for water resources.

II. Science Capabilities Necessary to Support Future Decision-Making

NOAA is well poised and has the legislative mandates to take a leadership role in developing ecological forecasts for coastal and marine environments that will yield significant economic and societal benefits to the Nation. Ecosystem-based management, a critical mission for NOAA, will not be possible without ecological forecasts. Through its comprehensive research investments, NOAA is developing the knowledge about ecosystem structure and function (i.e., physical, chemical, biological, and human interactions) necessary to develop ecological forecasts. These knowledge-based products include everything from applied research efforts to long-term observations. NOAA is also developing the infrastructure necessary to support ecological forecasts through the development of regional observing systems, coupled physical-biological models, sensors, and computational and data visualization/presentation capabilities. Together, these research and infrastructure capabilities have led to a suite of successful ecological forecasts with many more currently in development (see Appendix F).

The complexity of an ecosystem approach to management (EAM) demands a suite of complex, often linked, models, tools, and technology to provide a scientific basis for decision-making (e.g., linkage of airshed, watershed, water quality, and fisheries models). To achieve this full capability for ecosystem-based management, NOAA will need to develop integrated ecological forecasting systems over the next decade. As one approach, NOAA has proposed to establish or enhance existing regional centers for ecological forecasting that will be responsible for developing and transferring to the management community a suite of regionally-specific, integrated ecosystem modeling and ecological forecast tools to provide a scientific basis for the proactive and complex decisions that must be made at all levels of government. Having the regional centers and other NOAA ecological forecasting research programs associated or collaborating with the integrated ocean observing system (IOOS) will allow for regionally-coordinated planning for observations and models, and bring in regional user groups. Real-time integrated observing systems can also provide critically needed information to assess natural scales of variability, provide drivers for forecasting models, and provide data to test the accuracy and precision of forecasts.

The establishment of regional ecological forecasting centers will allow NOAA, in conjunction with other Federal, state, and local partners, to: 1) bring together research, monitoring, and modeling efforts to understand ecosystem composition, structure, and function, and to monitor ecosystem status and trends; 2) identify the requirements of the regional management community through workshops, focused studies, and continuous engagement; 3) track, coordinate, and integrate, where possible, ecosystem and socioeconomic modeling efforts within and external to NOAA; 4) identify critical gaps in knowledge for each region; 5) ensure those gaps are filled through the use of internal and external funding; 6) transition models, tools, and forecasts to operational status; and 7) provide predictions for management decisions at all ecosystem scales.

To build and reinforce NOAA's capability in ecosystem forecasting, a number of research, procedural, and tool needs have been identified along with a diverse set of challenges:

Research Needs

Research into anthropogenic stressors to ocean, coastal, and Great Lakes ecosystems has centered primarily on the effects from overfishing, habitat degradation, and declining water quality as well as natural physical hazards. Less is known about the linkages among climate change, food webs, physical-biological coupling, and ecosystem production dynamics. Understanding the fundamental knowledge base of ecosystem structure and function will allow NOAA to develop a suite of robust ecosystem forecasts addressing such issues as HABs, anoxia, fish distribution and abundance, beach closings, coral bleaching, and water quality and quantity. This research, by its very nature, is long-term. Specific types of research needs include:

- Definition of the time and space scales needed to capture the fundamental physical and biological drivers required for ecosystem forecasts.
- Measurements of the natural scales of variability regarding physical-biological coupling, food web dynamics, and ecosystem production.
- Definition of the observational needs to drive ecological forecasting models, assess the accuracy of model forecasts, and assess the impact of management decisions on resources and habitat quality.
- Development and testing of new sensors for physical and biological observing systems.
- Increased understanding of ecosystem composition, structure, functioning, and variability, and the connection between the abiotic and biotic components of coastal ecosystems. This includes an understanding of large-scale ecosystem drivers and an understanding of ecological communities, including interactions among species (including poorly-understood "hidden players" such as viruses,

microbes, and invertebrates), the physical environment, evolutionary history, and the "assembly rules," if any, by which ecosystems are formed.

- Increased understanding of ecosystem indicators and establishment of thresholds and breakpoints within ecosystems beyond which there are concerns or needs.
- Comprehensive process studies to understand the ecological mechanisms producing ecosystem patterns, and definition of ranges for key physical and biological parameters within ecosystem models.
- Integrated ecosystem studies involving observations, research, model development, and process studies. This will allow for increased understanding of connections among ecosystem drivers and functions as well as the ability to quantify key biological parameters and species dynamics necessary for biological models.

Procedural and decision support tool needs include:

- True interdisciplinary integration among scientists and agencies involved with the physical, geochemical, and biological aspects of ecosystem process and function.
- Strong connections, to integrate multiple technologies (e.g., satellites, observation platforms, ship surveys, biological sensors) associated with the development of IOOS and regional associations.
- Fully integrated, spatially explicit, coupled hydrodynamic and biological models with appropriate links to watershed and higher tropic level models on key ecological scales to support place-based ecosystem management.
- Robust physical modeling platforms to provide the foundation on which to embed biological models. As most of NOAA's ecological forecasts involve the movement of water (e.g., larval transport, HABs), an accurate physical hydrodynamic model (i.e., four-dimensional) is a necessity. Within this framework, various biological components could be added depending on the issue and forecast.
- Robust biological models capable of predicting distributions, behaviors, and interactions among biota (e.g., movement, predator/prey dynamics, growth, death, reproduction processes).
- Responses to data issues such as the integration of disparate data sources, establishing and enforcing data integrity, formatting output for appropriate decision support software, satellite data calibration and validation, archiving forecasts, as well as the data upon which they are based.

Challenges to fulfilling these needs include:

- Ecosystem science is highly complex.
- A series of predictions tailored to the local or regional needs are necessary due to a diversity of issues and users, as a single, one-size-fits-all forecast is not possible.
- Physical and biological components of ecosystems are grossly under sampled with current technologies and effort levels.
- Decisions regarding the types of forecasts for specific regions; locations where these forecasts will be operated; and who will run, maintain, issue, and fund the forecasts must be made.
- Disseminating the forecasts and informing the public must be balanced against

scientific uncertainties.
- Science-based assessments and information must be developed and disseminated to decision-makers in understandable and utilizable formats.

NOAA, as the primary Federal agency for ocean science supporting a variety of societal needs, is both an initiator and user of ecological forecasts. As an enabler, NOAA provides resources and personnel to collect the data, develop the forecasting products, summarize scientific results for decision-makers, produce assessments, and disseminate the synthesized results and information. The agency expects to use many of the forecasts to support its stewardship role. NOAA's ecological forecasting capability will be improved by the ability to simulate ecosystem complexity with coupled physical/biological models and data assimilation, and develop new models to predict ecological outcomes from alternative scenarios and facilitate the evaluation of management plans. These integrated forecasting systems will also foster the transition/operationalization of forecasts by assessing forecast accuracy, sensitivity, and error; defining acceptable levels of accuracy for proposed forecasts; enhancing risk assessment tools for management scenarios; linking socioeconomic cost-benefit analysis to ecological forecasts; developing testing and comparison metrics for forecasts; and developing methods to share, visualize, and communicate forecasts and uncertainty to user groups.

III. Partnerships Necessary to Effectively Address the Emerging Issues

The success of ecological forecasting depends on partnerships at all levels, from universities and local/state governments to other Federal agencies. The scale and complexity of ecological forecasts will require that NOAA improve its partnerships with external users and stakeholders and increase interactions among the NOAA programs and goal teams. NOAA must take advantage of its existing partnerships with other Federal agencies (e.g., IOOS, U.S. CCSP), international organizations (e.g., GEOSS, International Geosphere-Biosphere Programme), coastal states, and users of coastal ecosystems and their resources (e.g., commercial and recreational fishers). Strong partnerships will help decision-makers within and outside the government to identify the most critically needed forecasts and support efforts to build, test, and issue them. Some key elements of those partnerships are emerging but must be made stronger:

University partnerships (extramural research community): NOAA partnerships with the extramural research community are necessary to provide the research understanding and prototype ecological forecasts which will become the foundation for the development of "operational forecasts" within or outside of NOAA. There are several successful examples with NOAA's joint institutes and other major extramural research programs (e.g., GLOBEC, Ecology and Oceanography of Harmful Algal Blooms Program (ECOHAB), Monitoring and Event Response for Harmful Algal Blooms Program (MERHAB), Oceans and Human Health Initiative) where integration has occurred. NOAA also has an ongoing program dedicated to the development of ecological forecasts which encourages collaboration among university and NOAA scientists as well as coastal managers.

Local/state government partnerships and user community: The scale and complexity of ecological forecasts will also require that NOAA continue and improve partnerships with resource users and stakeholders. NOAA partnerships with decision-makers within local and state governments (e.g., managers of beaches, fisheries, shellfish, and water resources) are necessary for many reasons. State and local governments are one of the principal coastal management decision-makers and therefore the true users of the ecological forecasts. Information needs identified by managers will help define the types of forecasts produced, the level of accuracy required, and the most appropriate vehicles to disseminate the information. Other users include boaters, coastal landowners, recreational fishers, divers, surfers, the beach-using public, and commercial enterprises. Once forecasts are developed, these users can provide feedback to help identify needed improvements in forecast capabilities and to provide direction for future research. Local and state governments may also be involved in the actual transition, operation, and maintenance of developed forecasts. Establishing connections with the user community is critical during the development and transition of forecasts, and NOAA engages this community through a variety of mechanisms including workshops, surveys, networks, and participation in research (e.g., NOAA, 2002; Sturdevant, 2004; Hendee et al., 2006).

Federal partnerships (e.g., NASA, EPA, USGS, U.S. Corps of Engineers, National Science Foundation, USFWS): NOAA fosters partnerships with other Federal agencies to leverage expertise and funding and to collaborate on activities related to development of an ecological forecasting capability to support ecosystem management at a scale that is often larger than the purview of individual agencies. Some of these regional issues, including climate change, watershed-estuary-ocean interactions, coral reef health, habitat restoration, hypoxia, and HABs, can only be addressed through large-scale ecosystem based programs, the integration of multiple technologies, and large-scale coordination efforts such as IOOS and regional taskforce, alliance, and other collaborative endeavors (e.g., the Great Lakes Regional Collaboration, Gulf of Mexico Alliance, Mississippi River Watershed Nutrient Taskforce). NOAA is currently working with other agencies on the development of climate change forecasting centers and integrated earth systems frameworks for ecosystem management. The recently released U.S. Ocean Action Plan (CEQ, 2004) has also established a new ocean governance structure (i.e., the National Science and Technology Council's Joint Subcommittee on Ocean Science and Technology) aimed at integrating the activities of Executive Branch agencies regarding ocean-related matters and provides another avenue of coordination toward the development of ecological forecasts.

NOAA partnerships: NOAA is applying its extensive intramural and extramural research capacities and modeling expertise to assure successful development, validation, and demonstration of a wide variety of ecological forecasts. Ecological forecasts result from the integration of data, information, and models produced by multiple scientific disciplines, and thus reflect a multidisciplinary "Corporate NOAA." For example, a typical forecast may require collaboration among many NOAA programs, including

NOAA Satellites and Information Service (for satellite information), NOAA National Weather Service (for hydrology, wind fields, and rainfall data), and NOAA Research, NOAA National Ocean Service, and NOAA Fisheries (for interdisciplinary research, hydrodynamics, and food web information). In turn, one part of a forecast may be best operationalized within the NOAA National Weather Service, whereas another part may be best operationalized within NOAA National Ocean Service (e.g., Great Lakes forecasting system). This cross-line office and cross-goal aspect of research applications is central to the success of NOAA's ability to conduct ecological forecasts.

Within the agency, there are, however, several organizational and procedural challenges:

Organizational challenges include:

- Management of ecological forecast development through NOAA's Program Planning Budgeting and Execution System (PPBES) structure, which contains at least five programs working on components of ecological forecasting.
- Development of an 'end-to-end' approach for ecological forecasts that includes user identification, needs prioritization, funding of research and development, forecast product testing, planning for and funding of the transfer to application, and, when necessary, routine operation of the forecasts.
- Capacity-building to handle the accelerating increase in forecast products, if NOAA is the ultimate operational entity, or development of a robust procedure to assure the most appropriate transfer to all parties involved, if the operational entity is outside of NOAA.

Procedural challenges include:

- Prioritization of research, given the need for high risk, but potentially high payoff, research.
- Establishment of effective connections with the user community during the development and transition of forecasts.
- Definition of roles and responsibilities for ecological forecasting from a corporate level (e.g., who develops the forecasts, who receives and routinely runs the forecasts, what the users do with the forecasts, how resources are allocated, what is not done if there are no additional funds, the role of government versus the role of the private sector).

One of most challenging near-term issues for the agency is how to prioritize the development and transition to operations of the wide range and diversity of ecological forecasts currently in development. As evidenced in Appendix F, the ecological forecasting capability of NOAA is rapidly advancing on all fronts and the transition to operations of these forecasts will probably not be possible or warranted given funding constraints and other agency priorities. Prioritization among potential ecological forecasts will allow NOAA to invest resources and personnel in the most promising products. Potential prioritization criteria and questions include:

- Is the forecast a mandate for NOAA's coastal responsibilities?
- Is the forecast within NOAA's mission and goals?

- Should NOAA be the lead?
- What benefits will the forecast have after investment?
- Does investment in the forecast offer collaboration/leverage with other offices/agencies?
- Does investment in the forecast benefit multiple user groups?
- What is the time frame for development of the forecast?
- What is the overall level of investment needed?

NOAA has begun a path toward addressing some of these issues with the recent development of a research to application transition policy. The policy describes the process by which any research result, information, or tool should be transitioned into application. The policy calls for the creation of a Transition Board and of Transition Teams. Figure 3 outlines the proposed formalized process linking together program offices with various NOAA planning processes, which would help to prioritize the development and transition of new and ongoing ecological forecasts.

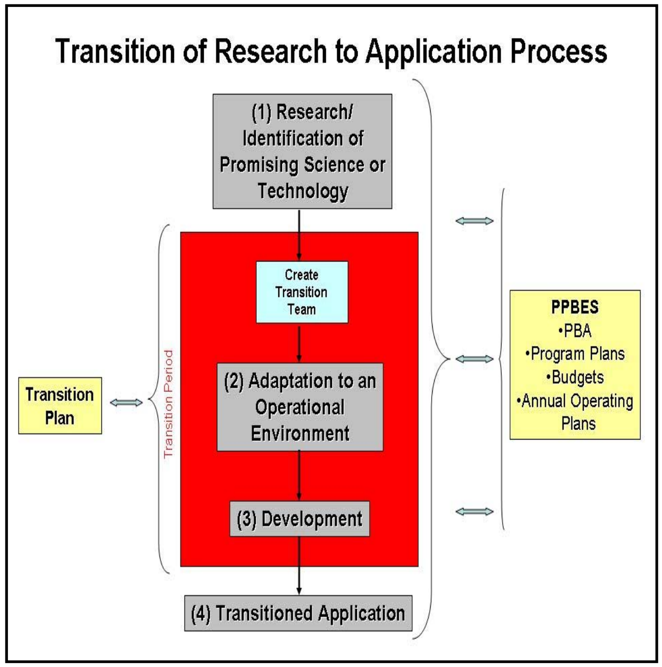

Figure 2. Proposed NOAA Transition Process outlining the steps involved with transitioning any research result, information, or tool into application.

IV. Benefits to NOAA, Constituents, and Society from this Effort

Maintaining ecosystem function and health will benefit U.S. society which demands coastal resources, such as uncontaminated fish and shellfish, and access to clean coastal waters. NOAA is charged by Congress and the Administration with specific mandates prescribed by law. Ecological forecasting will aid the agency in its stewardship responsibilities by providing information on future ecosystem-related problems, including feedbacks that affect human health, for which NOAA can respond and plan. NOAA has numerous ecosystem-related mandates, policies, treaties, and international agreement and at least 24 of these can be addressed or facilitated through ecological forecasts (see Appendix ????????????????????).

A key mission for NOAA is to develop scientifically sound ecological forecasts relevant to NOAA's mission, practical to its customers, and providing a necessary underpinning of ecosystem-based management. NOAA is developing ecological forecasts for coastal managers in an effort to help merge wide-ranging research and observation programs around this new and challenging science, which ultimately enriches the science-policy interface. Focusing on developing, testing, and applying ecological forecasts provides the coastal research and management communities with three benefits. First, ecological forecasts will help decision-makers better manage the Nation's coastal resources because they provide valuable information for better assessments that predict future conditions of proposed actions and the potential impacts of their decisions. Second, focusing on defining ecological forecasts needs will strengthen the link between research and management by tying management needs to a scientifically challenging agenda. Finally, the desire to build and improve ecological forecasts will help focus NOAA's coastal science agenda by assuring that NOAA's monitoring, research, and model development efforts are geared towards the needs of coastal managers who benefit from ecological forecasts.

This chapter has been an initial look at NOAA's current capability for ecological forecasts from near-real time to periodic forecasts and the needs, issues, and challenges that the agency will face in the next twenty years. Ecological forecasting is a very young and interdisciplinary field that capitalizes on NOAA's existing physical and biological expertise. NOAA must strive to integrate its research and provide the best forecasts as efficiently and effectively as possible. The authors hope this chapter will serve as a framework for facilitating the development of a robust ecological forecasting capability within NOAA and among its external partners as this field of science matures.

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Appendix F – Examples of NOAA Ecological Forecasts (Operational and in Development)

Ecological Forecast Categories/ Type	**Driver - Need**	**Frequency of Forecast**	**Spatial Extent of Forecast**	**Products - Outputs**	**User Community**	**Status**
Predicting movement of hazardous spills	-Disaster Planning -Living Resource Impact -Human Health Impact	-Near-real time	-Event Specific -Local -Regional	-Trajectory of movement -Risk to living resources and humans	-State managers -Federal managers -Emergency response personnel	-In Development -In Transition -In Operation
Forecasting the distributions, abundance, and health of living resources	-Stock Assessments -Living Resource Impact	-Seasonal -Scenario	-Regional -Species Distribution Range	-Species distribution maps -Species abundance -Probability of rebuilding overfished species -Projects distribution and abundance	-Fishery managers -Fishery management councils -State managers -Resource managers	-In Development -In Transition -In Operation
Forecasting the effectiveness and optimal placement of MPA's	-Stock Assessments -Living Resource Impact	-Scenario	-Regional -Local	-Species abundance, distribution, size structure and habitat maps -Optimal location of MPA's	-MPA managers -Resource managers	-In Development
Predicting coral reef health and recovery after disturbance	-Living Resource Impact	-Scenario	-Regional	-Species survival probability -Habitat maps	-Marine Sanctuary managers -Resource manager	-In Development
Predicting larval transport and survival	-Stock Assessments -Living Resource Impact	-Daily to weekly	-Regional	-Trajectory of movement -Probability of survival at a given location	-Marine Sanctuary managers -MPA managers -Fishery managers	-In Development -In Transition -In Operation
Predicting organism distributions based on habitat mapping	-Stock Assessments -Essential Fish Habitat -Living Resource Impact -Human health	-Scenario	-Local -Regional	-Species distribution maps -Habitat maps	-Local and state managers -Resource managers	-In Development -In Transition -In Operation

	impacts					
Development, persistence, movement and landfall of harmful algal blooms	-Living Resource Impact -Human health impacts	-Near real time -Daily -Scenario	-Local -Regional	-Trajectory of movement -Bloom identification -Probability of bloom initiation	-Local and state managers -Resource managers	-In Development -In Transition -In Operation
Coral bleaching forecasts	-Living Resource Impact	-Seasonal -Scenario	-Regional -Global	-Species survival probability	-Marine Sanctuary managers -Resource manager	-In Development
Effectiveness of habitat restoration	-Living Resource Impact - Essential Fish Habitat	-Seasonal -Yearly -Scenario	-Local -Regional	-Metric measuring restoration effectiveness	-Resource managers -State managers -Federal managers	-In Development -In Transition
Effectiveness of hydropower system modifications for survival of migrating fish	-Living Resource Impact -Endangered Species Act	-Scenario -Yearly	-Local	- Probability of individual fish survival -Probability of species recovery	-Local managers -State managers	-In Operation In Development
Projections of extinction risk for protected species	-Living Resource Impact -Endangered Species Act	-Scenario -Yearly	-Local -Regional	-Probability of species recovery	-Resource managers	-In Operation -In Development
Forecasts of the coastal ecosystem effects associated with upstream water management alternatives	-Living Resource Impact	-Daily -Seasonal -Yearly -Scenario	-Regional	-Metrics for impacts to the ecosystem under study	-City planners -Local managers -State managers -Federal managers	-In Development
Beach closure forecasting	-Human health impacts	-Near real time -Daily	-Local -Regional	-Probability of exceeding health standards	-Local managers -State managers	-In Development
Impact of climate change on coastal ecosystems	-Human health impacts -Living resource impact	-Months -Decades -Scenario	-Local -Regional	-Habitat inundation maps -Metrics for impacts to the ecosystem under study	-City and state planners -Local, state, Federal managers	-In Development
Forecasts of physical dynamics and their	-Living Resource Impact	-Near real time	-Regional	-Forecast maps and time-series of key physical parameters	-Resource managers -Federal managers	-In Development -In Transition

impacts on the ecosystem	-Human health impact	-Daily -Seasonal -Scenario		-Metrics for impacts to the ecosystem under study	-State managers	-In Operation
New non-native species introductions	-Living Resource Impact	-Scenario	-Local -Regional	-probability of species invasion	-State managers -Federal managers	-In Development
Drinking water quality and quantity	-Human health impact	-Scenario	-Local -Regional	-Probability of exceeding health standards	-Local managers -State managers	-In Development
Onset, extent and impact to living resources of hypoxia in coastal areas	-Living Resource Impact	-Near real time -Seasonal -Scenario	-Local -Regional	-spatial and temporal maps of hypoxia -metrics for impacts to living resources	-State managers -Federal managers	-In Development
Water quality forecasts	-Living Resource Impact -Human health impact	-Near real time -Daily -Seasonal -Scenario	-Local -Regional	-spatial and temporal maps of key water quality variables	-State managers -Federal managers	-In Development -In Transition -In Operation
Ice thickness/extent and ecological impacts	-Living Resource Impact	-Scenario	-Local -Regional	-Metrics for impacts to the ecosystem under study	-Resource managers	-In Development
Water quantity impact on living resources	-Living Resource Impact	-Daily -Seasonal -Scenario	-Local -Regional	-Metrics for impacts to the ecosystem under study	-State managers -Federal managers -Resource managers	-In Development
Forecast of shellfish toxicity	-Living Resource Impact -Human health impact	-Near real time -Daily	-Local	-toxin accumulation in shellfish	-State managers -Resource managers	-In Development